

Modular Switched Reluctance Machines to be Used in Automotive Applications

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Abstract—In the last decades industry, including also that of electrical machines and drives, was pushed near to its limits by the high market demands and fierce competition. As a response to the demanding challenges, improvements were made both in the design and manufacturing of electrical machines and drives. One of the introduced advanced technological solutions was the modular construction. This approach enables on a hand easier and higher productivity manufacturing, and on the other hand fast repairing in exploitation. Switched reluctance machines (SRMs) are very well fitted for modular construction, since the magnetic insulation of the phases is a basic design requirement. The paper is a survey of the main achievements in the field of modular electrical machines, (especially SRMs), setting the focus on the machines designed to be used in automotive applications.

Keywords—automotive applications, fault tolerance, modularization, segmentation

I. INTRODUCTION

Upon the definition of the modularity, different parts of a system comprise of smaller subdivisions (modules), which can be designed and manufactured separately, and only later connected together to work as a sole unit [1]. Modular systems can be designed to enable flexible substantiation of the components, which permit variations of the same product. Their design must be performed upon common set of rules [2]. Usually a modification performed within a module do not require also changes of the entire system [3]. This approach is frequently used in high technology products, as vehicles, electronics, computer systems, software, machineries, etc.

There are three broad fields in industry where the modularity can be employed [4]:

- in design, by means of a modular architecture, when conception starts from the functional elements, and finalizes via the interfacing of assemblies at the physical components of the entire system;

- in use, when the consumer decomposes the final product having in his mind to satisfy his need for an ease of use and for individuality of the product;
- in production, where modularity is twofold. The product itself can be built up of modules. And also the manufacturing process can be organized in a modular way, when the components are assembled off-line by a small and simple series of tasks, and then put together later on a main assembly line. This manufacturing approach is very closely connected with mass production [5].

In the case of electrical machines (EMs), which are not so complex and flexible systems as the cars for example, the modular design means that its main parts (the stator and the rotor) can have a segmental construction. This design not only enables easy manufacturing and maintenance, but assures in several cases also a high fault tolerance of the EMs [6].

The "modular motor" concept originally came out as a response to increasing safety and reliability requirements for the EMs. First time it was used in 1977 when a modular motor was patented by C.R. Carlson Jr. and M.J. Hillyer [7].

II. MODULAR DESIGN AND FAULT TOLERANCE

The modular design and fault tolerance are two very close concepts. An electromechanical system is fault tolerant (FT) if after any failure it can still work, even if at lower performances. Fault tolerance and high reliability can be achieved by using high quality components, by applying specific designs and control strategies, and by incorporating redundancy in the system. FT electromechanical systems are used in safety and operationally critical applications, where loss of life, injuries, environmental disasters or huge financial losses must be totally avoided (aeronautics, aerospace, automotive, medical, defense, power plants, etc.) [8].

Redundancy means that the system mirrors it's all operations, meaning that every operation is performed on two or more duplicate systems, in a way as if one fails, the other can take its role and keep the system work [9]. Redundancy can

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be assured in the simplest way by applying modular construction. In this case the system is a combination of series and parallel modules. Basically, redundancy of EMs can be solved by placing multiple machines on the same shaft (assuring the so-called parallel redundancy). This approach can be useful also for the best power fitting of the coupled machines in exploitation: when higher power is required, an extra segment (machine module) can be started. It should be mentioned, that this approach is the most rudimental FT solution, since the system complexity and costs are high. Furthermore, redundancy may not be a good FT increase solution in the case of applications which have severe space and/or mass restrictions [10].

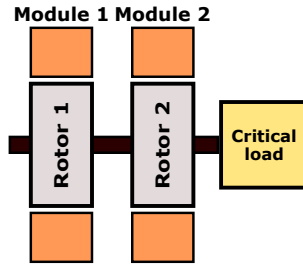


Fig. 1 Multiple modular motor drive with redundancy [10]

Upon another FT increase approach, multiple-phase modular EMs can be applied. In such case, an independent phase can be considered as a single module. The operation of each module must have minimal impact upon the others. So, if a module is failing, the others can continue to still operate unaffected. This approach can be extended to both the machine and the power converter [11], [12].

Based on a remarkable idea of N.R. Brown the EM and power converter modules are integrated together to increase the compactness and easy reparability of the machine-converter assembly. The so-called integrated modular motor drive (IMMD) concept can be seen in Fig. 2 [13]

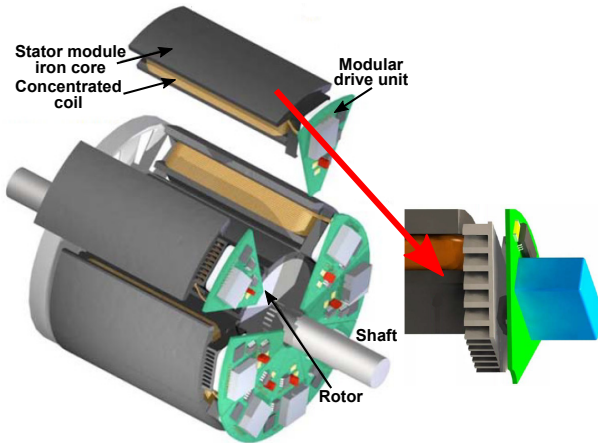


Fig. 2 The integrated modular motor drive (IMMD) concept [13]

The main FT requirements are inherently met only in switched reluctance machines (SRMs), since their phases are only lowly magnetically coupled, and they are supplied from independent half-bridges. Therefore, when highly FT machines has to be developed, the classical SRM must be the starting point [14].

III. ORIGINS OF MODULAR ELECTRICAL MACHINES DEVELOPED AT TECHNICAL UNIVERSITY OF CLUJ

The history of building modular EMs is very hard to study due to the deficient access the greatest part of papers published before the 1980's. Therefore, in the section the focus will be set on the modular EMs developed at the Technical University of Cluj (Romania). In a part of these studies also the author was involved.

A typical EM which can be built only from modules is the hybrid linear stepper motor (HLSM), shown in Fig. 3 [15].

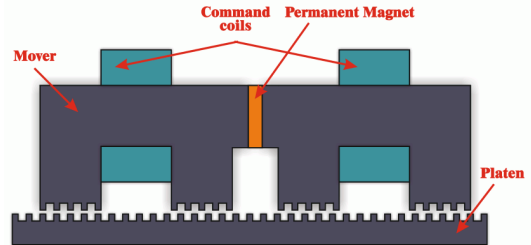


Fig. 3 Hybrid linear stepper motor [16]

The HLSM fundamentally is a variable reluctance (VR) permanent magnet (PM) excited synchronous motor. It comprises of a mover (also called forcer) and a stationary platen. The platen is a passive equidistant toothed steel bar. The mover is made up of two U-shaped iron cores, having round their yoke concentrated coils. The legs (poles) of the modules are toothed, having the same tooth pitch as the platen. Between the two modules a PM is placed. The four poles of the motor are spaced in quadrature, in a way as at a time the teeth of a single mover pole can be aligned with the platen teeth. When one of the modules is supplied, the resulting magnetic flux tends to concentrate the PM flux in one pole of that module. The teeth of this pole will be aligned with the platen teeth due to the VR principle. By sequentially supplying with bipolar current pulses the two command coils, an incremental linear movement can be achieved in both directions [15], [16].

This basic structure of the HLSM was further developed by an innovative modular structure, which enabled a flexible construction of the HLSMs of any force and step length [17], [18]. The mover of the machine comprises of magnetically separated modules (like that given in Fig. 4), having a PM, two salient toothed poles and a coil.

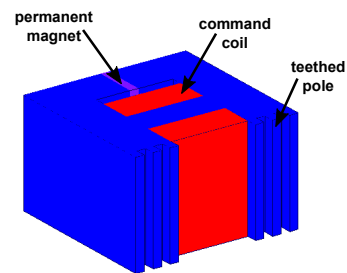


Fig. 4 A mover module [17]

A simple three-phase HLSM variant built up from such modules is given in Fig. 5. As it can be seen, non-magnetic spacers are placed among the modules to assure the adequate relative shifting between them.

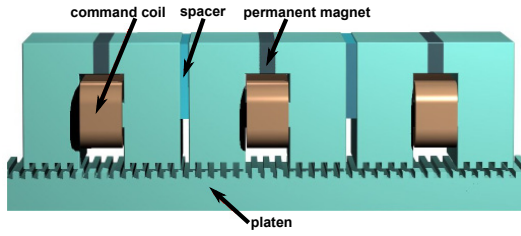


Fig. 5 A three-phase modular HLSM

The VR principle based work of the motor is simple. If a module is inactive (its command coil is not supplied), the magnetic flux generated by the PM is crossing the core segment placed below the PM (see case 1 in Fig. 6). If the command coil is supplied (case 2), the module becomes active, since the flux of the PM is forced to pass through the air-gap and platen, and tangential traction force is generated. This will move the forcer one step further, in a position where the teeth of the module are aligned with those from the platen. By consecutively supplying the command coils of the motor, linear motion can be achieved [17], [18].

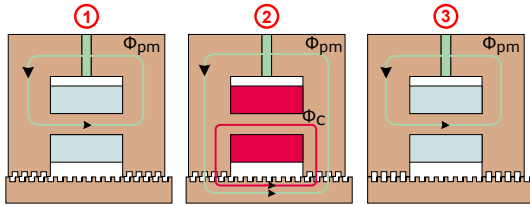


Fig. 6 The working principle of the modular HLSM

This constructional approach was further advanced for developing surface [19], and both rotational [20] and linear transverse flux motors (TFMs) [21].

IV. MODULAR ELECTRICAL MACHINES OF DIFFERENT TYPES

When modular construction of EMs comes in discussion, the segmentation of the wound stator core must be taken first into account. Here, only a few representative modular constructions will be given from the numerous construction variants cited in the literature.

A. Modular Permanent Magnet Synchronous Machines

A typical stator segmentation of a permanent magnet synchronous machine (PMSM) is given in Fig. 7 [22].

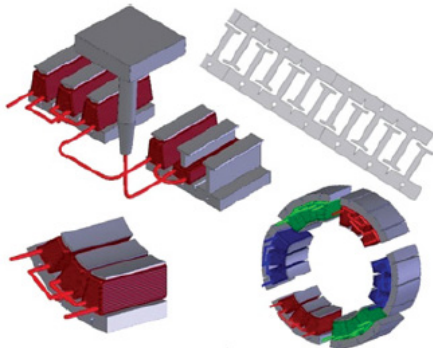


Fig. 7 PMSM stator modules with concentrated windings [22]

The iron core is designed in a way as to minimize the scrap of laminated steel, and to obtain a design with large tooth width and small tooth tips. Three teeth with concentrated coils around them comprise a module. By using six such modules a three-phase 18-slot stator can be assembled, which can be used in a PMSM having a 16-pole rotor. This modular stator structure has diverse advantages, as that the concentrated windings are rigidly packed with a high slot fill factor. Supplementary, these windings have short end-coils, which makes these constructions superior to those with usual distributed windings, mainly in low-speed applications [22].

In several cases the EMs modules are, or must be made of soft magnetic composites (SMCs). SMCs comprise of isotropic iron powder particles embedded in an insulating film coating. The cores made of SMCs can be manufactured of any three-dimensional shape, and have very low losses [23].

An example for building the stator of a PMSM from SMC modules is given in Fig. 8 [24]. Since each module can be wound separately with concentrated coils, the manufacturing is very simple. The modular construction approach also in this case enables high flexibility in phase number and control strategy selection. Due to the SMC technology, special pole shoe and yoke shape designs can be applied. Also, a very good air-gap space usage can be achieved, which can lead to an increase in torque generation, a basic requirement in automotive applications, too.

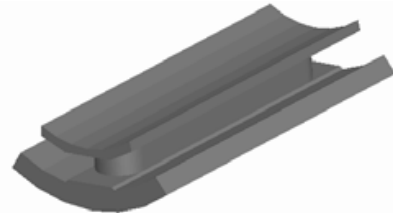


Fig. 8 SMC made stator module of a PMSM [24]

Another example for the segmented stator PMSM is that proposed by C. Tong. The stator comprises of modules having salient poles with concentrated coils, as it can be seen in Fig. 9. The fractional-slot coils are forming a four-phase alternate-teeth winding, which assures a very good thermal and physical isolation of the phases, an important issue in FT applications, like the automotive one [25].

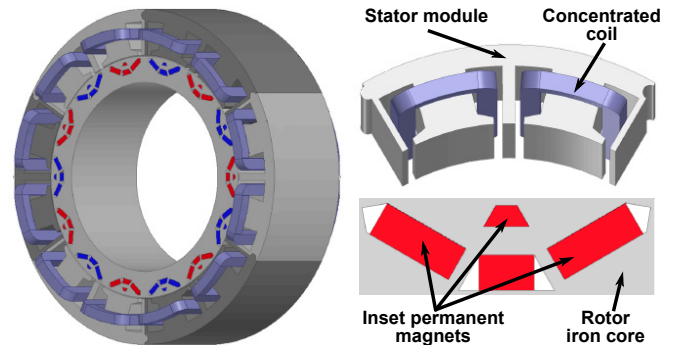


Fig. 9 Modular stator PMSM [25]

The segmentation of the PM EMs to improve their FT can be performed also on the axial direction [26].

B. Transverse Flux Electrical Machines

TFMs are EMs which can be built up only modularly and almost all the cases only of SMCs. They are among the newest EMs developed. Their main distinctive feature is the transverse direction flux path and the homopolar magnetomotive force (mmf) produced by a ring type coil, in which the current flows in parallel to the rotating direction of the machine. In the air-gap of the TFM the mmf is modulated by a specific pattern of stator poles to interact with a heteropolar pattern of rotor poles, with or without PMs. The TFM has some notable advantages, as their pole number can be increased (and their synchronous speed diminished) without reducing the mmf per pole, and they have greater power density than any classical EM [27].

Due to their complex structure, numerous variants, with and without PMs, were proposed in the literature [28]. Their direct-driven variants seem to be very suitable for electrical traction applications [29], [30], [31]. Here, in Fig. 10 only two structures are presented.

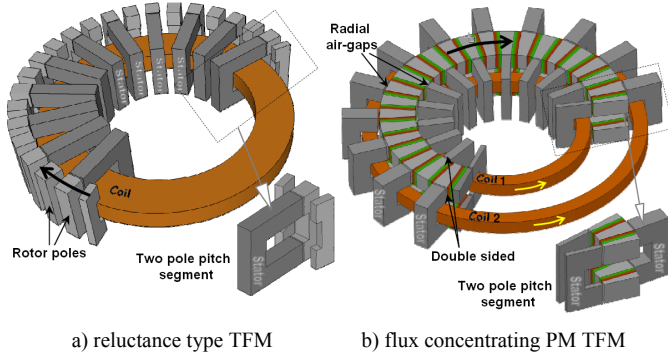


Fig. 10 Two modular TFM variants [31]

In Fig. 10a a reluctance type TFM with passive rotor and an armature winding of the stator is given. An example of the more typical PM TFMs is shown in Fig. 10b. It is of flux concentrated PM type, and it comprises of two series connected ring-shape coils per phase. To match the direction of the armature flux with the PM magnetic flux, the two coils are connected in series in a way as to have their generated flux added. In the figures, the two pole pitch segments (modules) for both variants are zoomed, to be more easily distinguished.

C. Modular Flux Switching Permanent Magnet Machines

The flux switching (FS) PM machine is also a newcomer among the EMs. This VR machine comprises of U-shaped iron core modules disjointed by PMs, alternatively magnetized on the circumferential direction, as it can be seen in Fig. 11. The concentrated stator coils are wound around one leg of adjacent modules and the PM placed between them [32], [33]. The FS machine has the advantages of the robustness and of having both mmf sources (the armature windings and the PMs) on its stator. Despite the low torque production area in the air-gap worthy of to its double saliency, it can achieve high torque densities due to its very good magnetic flux concentration capability. In addition, it has a passive salient poles robust rotor [32].

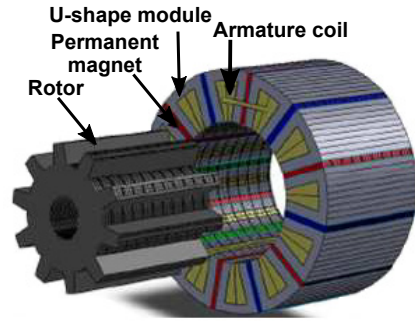


Fig. 11 Flux switching PM machine [33]

Designing the FS machine in a multi-phase FT variant, it can be successfully used in diverse safety-critical applications, among them also in automotive ones [34].

Unfortunately, the high flux concentration and power density of the FS PM machines is accompanied by significant iron core losses. These losses can be reduced without significant output torque decrease by segmenting also its rotor, as it can be seen in Fig. 12. The rotor modules are lamination stacks separated by flux barriers, made of low permeability material. [35].

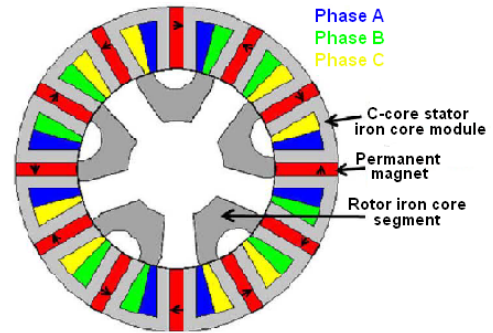


Fig. 12 Segmented rotor FS PM machine [35]

The effect of the segmented rotor on the magnetic field distribution in the machine can be seen in Fig. 13. In the second case, the flux lines are a little bit shorter, and better flux concentration is achieved beside the decrease of rotor iron core volume.

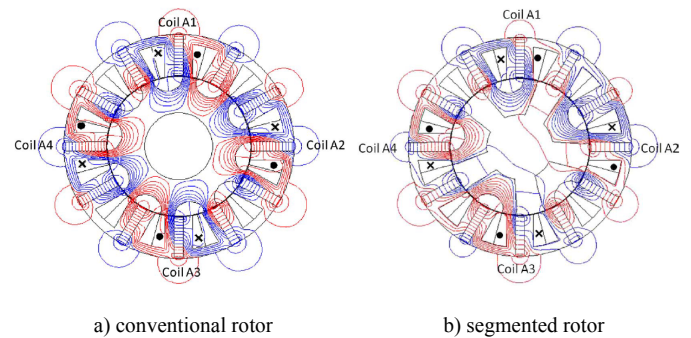


Fig. 13 Magnetic flux distribution in FS PM machines [35]

In a similar way also the flux reversal (FR) PM machines can be built up with segmented stators [36].

V. MODULAR SWITCHED RELUCTANCE MACHINES

The simplicity of the SRMs makes them easy to be constructed in modular versions. They can have segmented stator, rotor or both armatures. By iron core segmentation the magnetic flux in the modules can be increased, resulting in higher torque. Moreover, the flux paths are shorter, leading to less iron core losses. The main challenge for designing such machines is the way as to join the modules for keeping the high robustness of the classical construction SRMs.

A. Modular Stator Variants

In case of modular-stator type SRMs, the stator is usually made of several modular C-shaped or E-shaped electrical steel laminated segments.

C. Lee made significant efforts to reduce by 20% both the copper and iron requirements of a two-phase SRM by applying E-shaped stator iron core modules (see Fig. 14) [37].

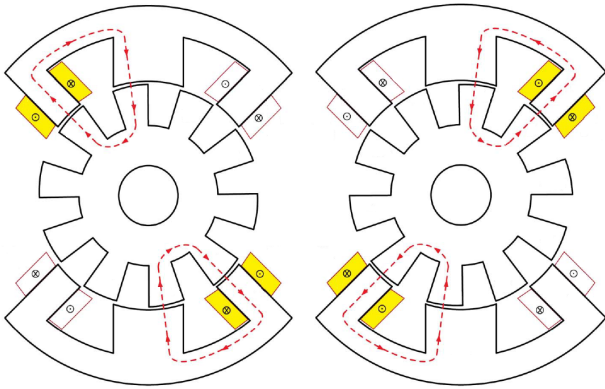


Fig. 14 Two supplying sequences of the modular two-phased SRM [37]

These have three poles, two at the ends, having concentrated coil wound around, and a center one with double cross section, having no windings. The two modules can be joined together either by prefabricated plastic molding, or by a sleeve-type fixture. This construction enables a very good usage of the iron core, since the middle pole is passed thru all the time by the magnetic flux, as it can be seen in the two supplying sequences given in Fig. 14 [37].

The above presented structure was improved by H. Eskandari et al. by increasing the number of stator modules from 2 to 3 (as it can be seen in Fig. 15), mainly to increase the developed torque and the mechanical strength of the stator, and also to reduce its vibrations, a critical issue in automotive [38].

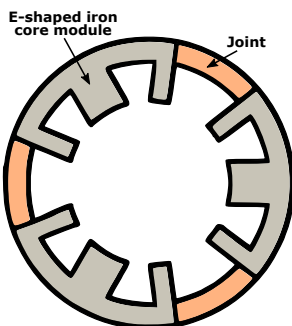


Fig. 15 Improved 9/12 poles modular two-phased SRM [38]

The segmented stator SRM can be built up also with external rotor. The variant proposed in [39] has 6, basically E-shaped stator iron core modules, each with four poles, and a solid 22 poles outer rotor (as it can be seen in Fig. 16). It was demonstrated in the paper, that this SRM, designed for hybrid electrical car applications, can produce over 20% higher torque as its classical SRM counterpart.

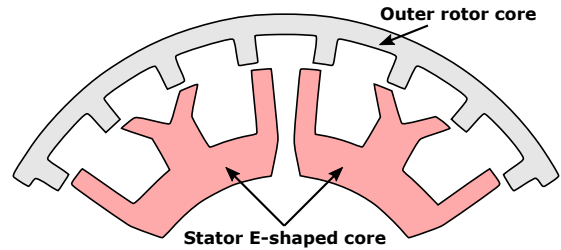


Fig. 16 Outer rotor segmented stator SRM topology [39]

A segmented stator SRM was developed also at the Technical University of Cluj (Romania) by M. Ruba [40], [41]. The four-phase machine shown in Fig. 17 has 16 stator and 14 rotor poles.

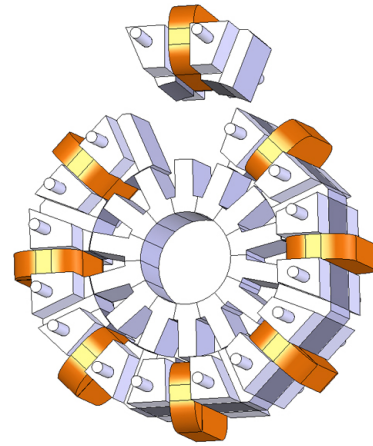


Fig. 17 The segmented stator SRM [40]

The stator is built up of 8 U-shaped iron core modules, as that in Fig. 18. The coil is wound round the yoke. Two adjacent modules are separated by a non-magnetic spacer. These both assure the adequate shift of the modules, and a good magnetic separation. The rotor is a usual salient pole passive one.

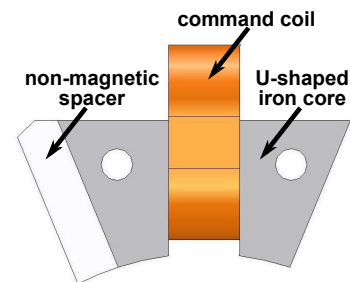


Fig. 18 A stator module of the SRM given Fig. 17

The main advantages of this SRM developed for automotive applications are the easy and cheap manufacturing, high FT [42], less iron losses and the opportunity of a fast replacement of a damaged module in case of a coil failure.

B. Segmental Rotor Concepts

In early designs of SRMs, segmented rotor variants were taken from synchronous reluctance motors (SyncRels), where the developments were focused on the rotor magnetic circuit [43]. There were attempts to use axially laminated anisotropic (ALA) rotors also in the case of SRMs [44], [45]. The rotor comprised of axial laminations of different sizes interleaved with nonmagnetic material sheets, as shown in Fig. 19.

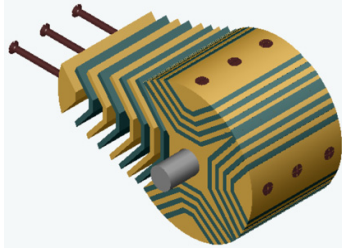


Fig. 19 Axially laminated anisotropic segmented rotor

Upon a newer approach, the rotor of the SRM was built up of iron core segments. This structure, given in Fig. 20, was patented by G.E. Horst for a two-phase unidirectional SRM [46]. The main advantage of this SRM variant is, as it is depicted in the patent description, its greater torque density.

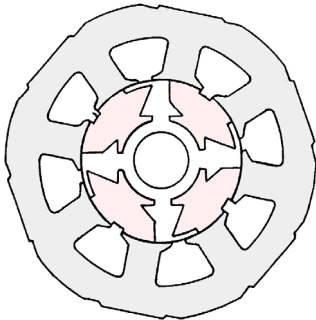


Fig. 20 The iron cores of a segmental rotor SRM [46]

A newer, three-phase bidirectional SRM variant was proposed by D.C. Mecrow (shown in Fig. 21). The 8 rotor modules are attached on a steel shaft, made of non-magnetic steel, to disable the pass of the magnetic flux between the modules. The rotor segments require both circumferential location and retention against axial and radial forces, which is a common shortcoming of the segmental rotor constructions [47].

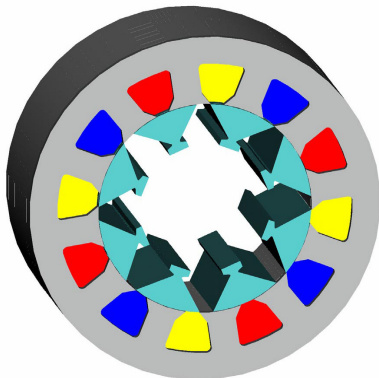
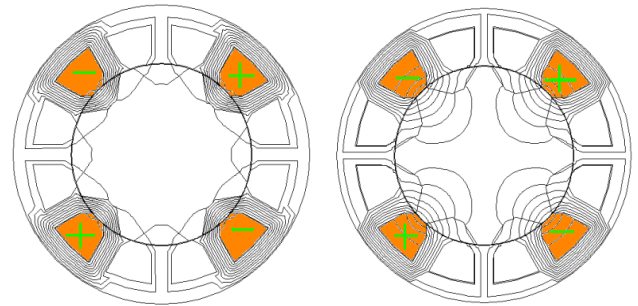


Fig. 21 Segmented rotor SRM [47]

This 12/8 poles SRM variant, as most of the modular rotor variants, has an important advantage over the classical salient pole design, that the flux path through the rotor is shorter. Any magnetic flux path only encloses a single stator slot, as it can be seen in Fig. 22.



a) aligned position

b) unaligned position

Fig. 22 Flux lines in the segmental rotor SRM [47]

In [47] the authors compared the SRM given in Fig. 21 with both the axially laminated and the usual salient pole design. It was shown that higher torque per unit magnetic loading can be produced with it due to the better magnetic utilization. When one phase is supplied by unipolar current, 8 of the 12 stator poles are active (as compared with 4 in the case of classical SRM). Hence the motor carries much more magnetic flux, and more torque is generated.

Axial flux SRMs were developed also with segmented rotor. In one of such machines the inner stator has poles on both faces and the axis of the toroidal windings are on the radial direction. The machine is closed on its both ends by two segmented rotors [48].

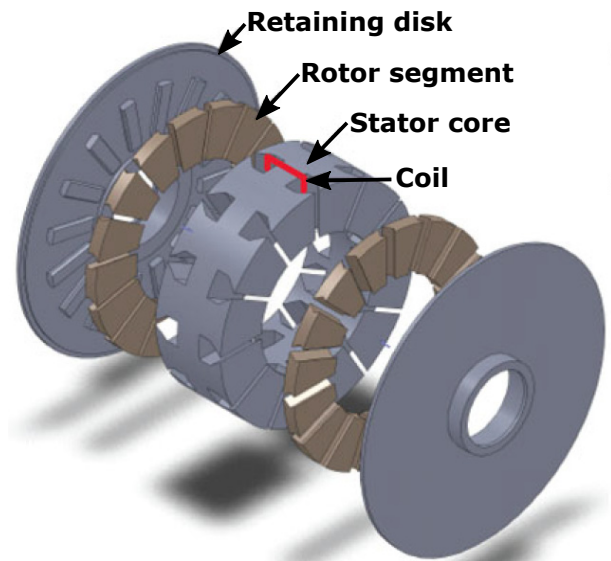


Fig. 23 Modular axial flux SRM [48]

Upon another approach, the rotor segments of the axial flux SRM are fully inserted inside the non-magnetic material, thus enabling the possibility of high speed application. A simple such SRM with a single stator is proposed in [49]. Other axial flux SRM variants were developed also for automotive traction [50] and more electric aircraft applications [51].

C. Doubly Segmented Construction

A doubly segmented SRM was proposed by M. Diko (see it in Fig. 24) [52]. Its stator comprises of E-shaped modules with a concentrated coil on their yoke, like that given in Fig. 18. The rotor has segments as the SRM in Fig. 21.

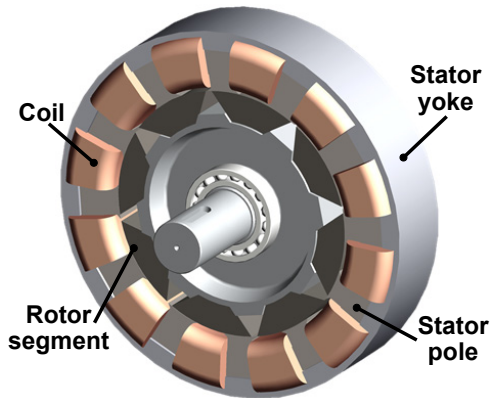


Fig. 24 Doubly segmented SRM [52]

The three-phase machine has a 12/8 poles structure. It is water-cooled by means of a spiral, and is proposed to be used in an electric mini truck. The main nameplate data of the SRM are: 20 kW rated power, 5.000 r/min rated speed, 300 V dc link voltage, and 250 A maximum current. The SRM has very short magnetic flux paths and increased FT.

In [53] X. Xue proposed an axial flux SRM segmented on both armatures, having a yokeless rotor (see it in Fig. 25). Its stator is built up of 8 C-shaped module, each having two coils. The 10 rotor poles are connected to the shaft by simple support branch. Thus, the rotor had low mass and inertia. Hence, the SRM is well suited for applications requiring good dynamic behavior, as wind turbine generators or automotive applications.

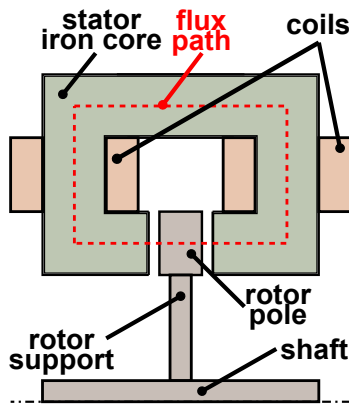


Fig. 25 Doubly segmented yokeless rotor SRM [53]

A. Labak proposed a similar axial flux SRM with modules on both its stator and rotor. The stator comprises of 16 C-shaped iron core modules, each having a concentrated winding on it. The active parts of the rotor are the so-called cubes, embedded in an Al disc having the shaft in its middle, as it can be seen in Fig. 26. Due to its optimized flux paths, the machine has high efficiency, and thus it is proposed for electrical vehicle powertrain applications [54].

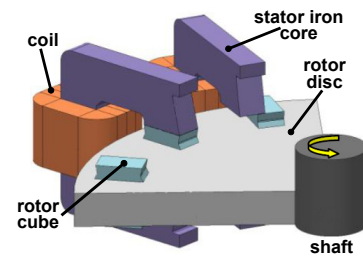


Fig. 26 The pancake-shaped doubly modular SRM [54]

A very compact in-wheel axial-flux segmented SRM was proposed by P. Andrada (see Fig. 27) [55].

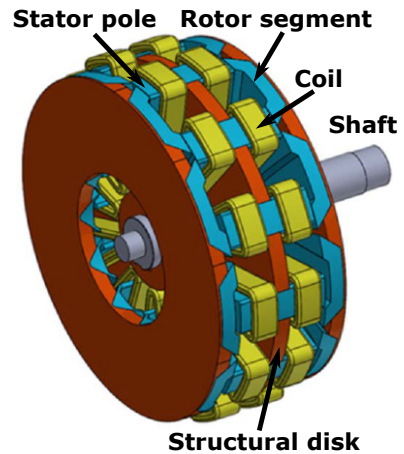


Fig. 27 The in-wheel segmented rotor axial SRM [55]

As it can be seen, the stator is made of wedge-shaped iron core modules having concentrated coils wound round them. The segments are kept together by a nonmagnetic structural disk. The stator is sandwiched by two specially segmented rotors, also placed on nonmagnetic support plates. The iron core segments are made of SMC. The SRM has very short magnetic flux paths without flux reversal. It was particularly developed to direct drive light scooters or motorcycles.

An axial flux doubly segmented SRM was also developed by Z. Pan [56]. Each of the 12 C-shaped stator modules, placed directly on the housing, have two together connected coils. The rotor comprises of 8 equally shifted active segment, as it can be seen in Fig. 28. The highly compact machine has good efficiency due to the low iron and copper losses.

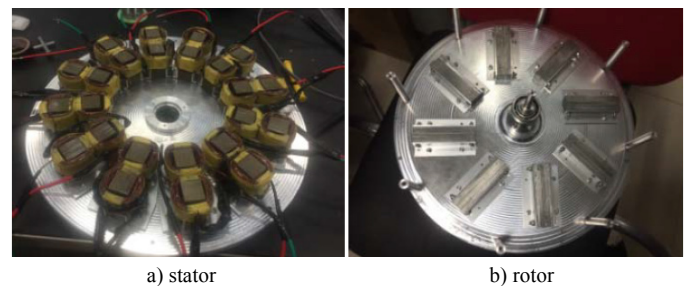


Fig. 28 Doubly segmented axial SRM developed by Z. Pan [56]

Researchers at University of Oxford developed a two-phase, axial flux, high speed SRM with modular stator and twin segmented rotor [57]. The stator modules are of

wedge-shape, and each one has wound round a concentrated coil. The segmental rotor is given in Fig. 29.

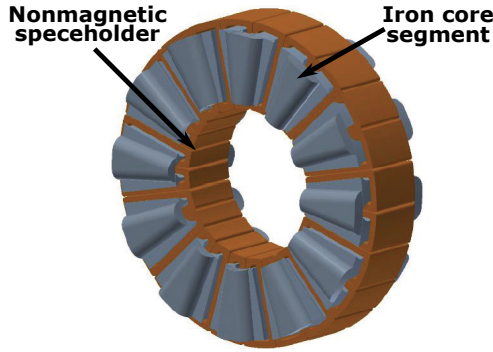


Fig. 29 The rotor of the high-speed axial flux doubly segmented SRM [57]

All its iron core segments are made of SMC. The machine can achieve 20,000 r/min and its power density is 7 kW/kg. It was designed for a hybrid-electrical sport car traction application.

More complicated, having more iron core, but probably more robust is the SRM variant proposed by W. Ding in [58]. The axial flux doubly segmented SRM is a further development of the SRM presented in [59], which had simpler E-shaped stator iron core modules. The proposed SRM has 6 E-shaped stator segments, each with 2 concentrated coils wound on its yoke. The rotor is also segmented in a similar way as the stator, as the poles cross section concerns (the middle pole has double cross section area as those at the ends). In the paper, the proposed SRM was compared with a classical construction SRM and with a similar axial flux segmented stator variant, but having non-segmented rotor. All of them had the same external diameter and axial length. The proposed variant had the lowest iron mass, the highest torque, and the greatest power and torque densities [58]. Therefore, it can be a very good competitor for the EMs used in automotive applications.

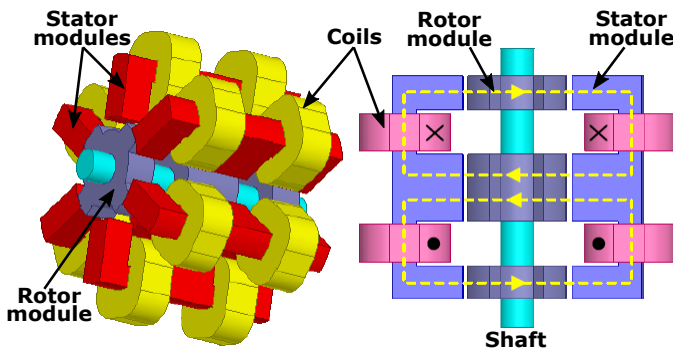


Fig. 30 The axial flux doubly segmented SRM [58]

This machine, as also that proposed in [59], can be extended on the axial direction by adding more poles or modules to fit the SRM to any power requirement.

The doubly modular construction approach was also applied for linear SRMs. Several motor modules, which can generate identical traction forces, can be coupled together to achieve the force requirement imposed of different applications

[60], [61]. Such linear SRMs are well fitted for ropeless elevator drive applications, but they can be used also in some car appliances [62].

D. Multilayer SRMs

Upon another approach, the segmentation of the SRM is performed on the axial direction. Such construction was firstly proposed by Afjei [63]. The multilayer SRM comprised of 3 magnetically independent modules (phases, or so-called layers), which are like a standalone classical SRM. A particular feature of the modules is that they have identical number of poles (8) on both armatures and all their coils form a phase of the machine. The rotor modules are shifted by 15° relatively to the neighbored modules (as it can be seen in Fig. 31).

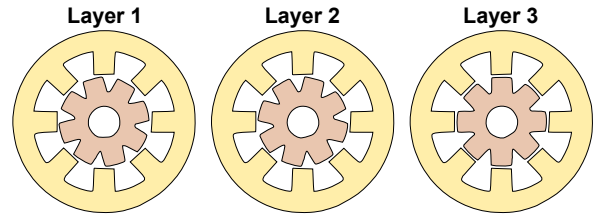


Fig. 31 The iron cores of the three-layer SRM

Placing each phase of the SRM on separate layer, larger phase advancements can be achieved since the flux paths corresponding to each phase are totally independent. This enables a faster phase current build-up, which is very important in high speed automotive applications. Supplementary, higher torque can be obtained as compared with a same sized classical 12/8 poles SRM [63].

Upon this multilayer concept, SRMs having low torque ripple can be constructed. In [64] a 3-phase, 7-layer SRM is proposed. All the 6-poles stator layers are placed un-shifted, and has 6 concentrated coils. The seven 4-poles rotor layers are shifted by 12.7°. At the same time three layers are active (having supplied coils). The torque ripple is reduced due the same effect as in the case of skewed rotor EMs [65], [66].

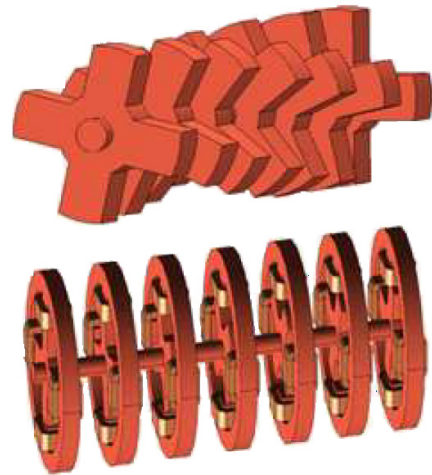


Fig. 32 The 7 layers SRM [64]

As described in a US patent proposal, also the axial flux SRM can be built in a multi-layer variant, as shown in Fig. 33

[67]. This modular construction enables a very good adaption of the machine to the torque requirements of various applications.

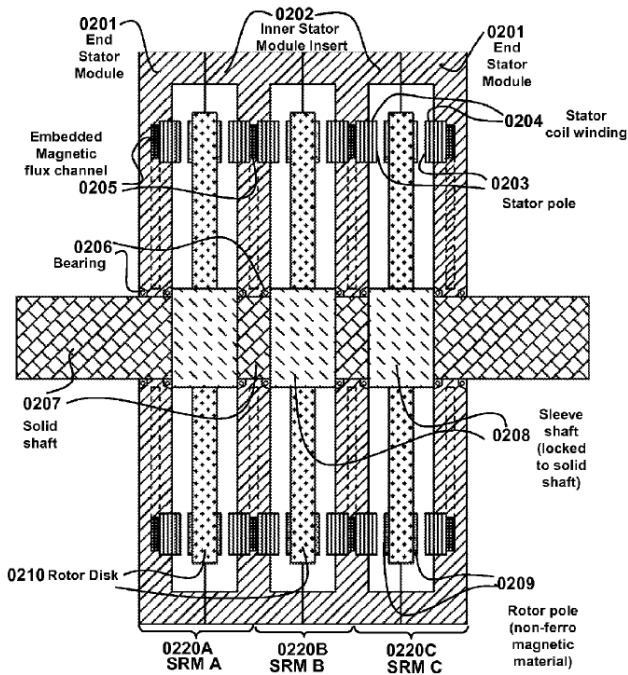


Fig. 33 Multilayer modular axial flux SRM [67]

E. Permanent Magnet Boosted Modular SRMs

In the literature, there are proposals to improve the performances of SRMs by inserting PMs, mainly in their stators.

One of the simplest ways to perform this was by replacing the non-magnetic spacers from the modular SRM given in Fig. 18 with ceramic PMs, as shown in Fig. 34.

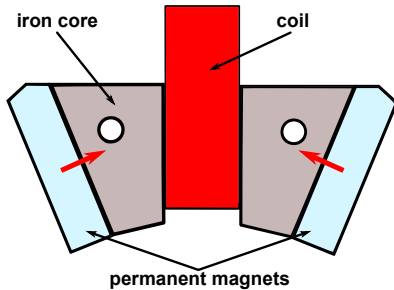


Fig. 34 The PM placements and magnetizations [68]

As it can be seen, the PMs are magnetized alternatively, the magnetization direction being perpendicular to their face in contact with the poles of the stator segment. Upon the study of this modular SRM, it was concluded, that the developed mean torque is greater by near 27% as in the case of the SRM considered as starting point. Unfortunately, also the torque ripples intensified with near 25% [68].

Modules containing both coils and PMs, as those given in Fig. 4, were applied also for a hybrid SRM by P. Andrada [69] and later by W. Ding [70].

The 12/8-pole, three-phase, modular stator hybrid excited SRM with 6 U-shaped stator modules, having a PM placed between the two poles of a stator segment is given in Fig. 35. The working principle is like that described by means of Fig. 6.

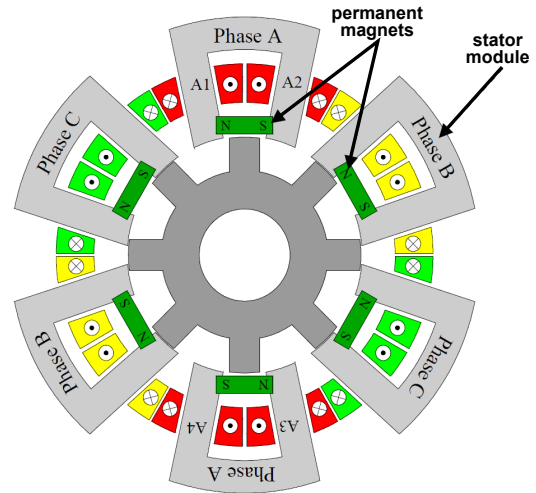


Fig. 35 The modular stator hybrid excited SRM [70]

The above detailed topologies, beside increased FT, have higher efficiency and can be rated at higher power than conventional SRMs of the same size. A major advantage of these machines is the lack of cogging torque due to the placement of the PMs, an important requirement also in automotive applications [69].

An interesting bearingless segmental stator VR PM motor is proposed in [71]. The machine, only by its stator coils, can assure both the contactless levitation and the rotation of the rotor. The stator comprises of 4 E-shaped magnetic iron cores, each having a concentrated coil wound round its middle pole. The disc shape rotor has 8 buried, and alternatively radially magnetized PMs. The 3 of the 6 degrees of freedom of the rotor can be controlled via the reluctance forces generated by the four coils. The main advantage of this motor is that the radial forces generated by dc currents are not depending on the rotor angle and in consequence a decoupled generation of motor torque is possible.

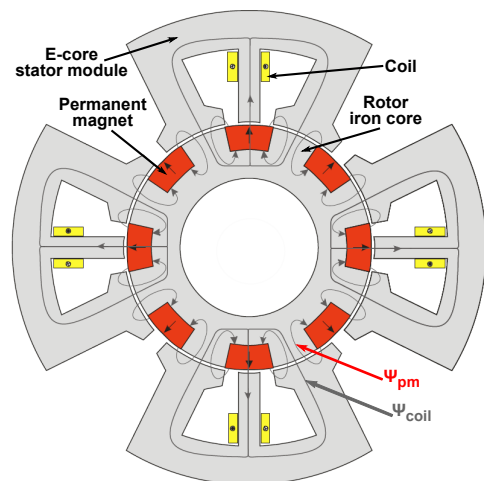


Fig. 36 Bearingless modular PM motor [71]

REFERENCES

- [1] C.Y. Baldwin, K.B. Clark, *Design rules: The power of modularity*. Cambridge (USA): MIT press, 2000.
- [2] U. Asan, S. Polat, S. Serdar, "An integrated method for designing modular products," *Journal of Manufacturing Technology Management*, vol. 15, no. 1, pp. 29-49, 2004.
- [3] J. Paralikas, A. Fysikopoulos, J. Pandremenos, G. Chryssolouris, "Product modularity and assembly systems: An automotive case study," *CIRP Annals - Manufacturing Technology*, vol. 60, no. 1, pp. 165-168, 2011.
- [4] J. Pandremenos, J. Paralikas, K. Salonitis, G. Chryssolouris, "Modularity concepts for the automotive industry: a critical review," *CIRP Journal of Manufacturing Science and Technology*, vol. 1, no. 3, pp. 148-152, 2009.
- [5] G.G. Rogers, L. Bottaci, "Modular production systems: a new manufacturing paradigm," *Journal of Intelligent Manufacturing*, vol. 8, no. 2, pp. 147-156, 1997.
- [6] I. Benția, M. Ruba, L. Szabó, "Modular electrical machines – A survey," in *Proceedings of the International Scientific Conference MicroCAD '2010*, Miskolc (Hungary), 2010, pp. 87-92.
- [7] C.R. Carison, M. Hillyer, "Modular motor," US 4056749 A patent, 1977.
- [8] L. Szabó, M. Ruba, E. Kovács, V. Füvesi, "Fault tolerant modular linear motor for safe-critical automated industrial applications," *Journal of Computer Science and Control Systems*, vol. 2, no. 1, pp. 128-131, 2009.
- [9] D.J. Smith, *Reliability, Maintainability and Risk: Practical Methods for Engineers*. Oxford (UK): Butterworth-Heinemann, 2017.
- [10] N. Ertugrul, W. Soong, G. Dostal, D. Saxon, "Fault tolerant motor drive system with redundancy for critical applications," in *Proceedings of the 33rd Annual Power Electronics Specialists Conference (PESC '2002)*, Cairns (Australia), 2002, pp. 1457-1462.
- [11] A.G. Jack, B.C. Mecrow, J.A. Haylock, "A comparative study of permanent magnet and switched reluctance motors for high-performance fault-tolerant applications," *IEEE Transactions on Industry Applications*, vol. 32, no. 4, pp. 889-895, 1996.
- [12] G.-J. Su, J.W. McKeever, K.S. Samons, "Modular PM motor drives for automotive traction applications," in *Proceedings of the 27th Annual Conference of the IEEE Industrial Electronics Society (IECON '2001)*, Denver (USA), 2001, pp. 119-124.
- [13] N. Brown, T. Jahns, R. Lorenz, "Power converter design for an integrated modular motor drive," in *Conference Record of the 2007 IEEE Industry Applications Conference & 42nd IAS Annual Meeting (IAS '2007)*, New Orleans (USA), 2007, pp. 1322-1328.
- [14] M. Ruba, L. Szabó, L. Strete, I.A. Viorel, "Study on fault tolerant switched reluctance machines," in *Proceedings of the 18th International Conference on Electrical Machines (ICEM '2008)*, Vilamoura (Portugal), 2008.
- [15] I.A. Viorel, L. Szabó, *Hybrid Linear Stepper Motors*. Cluj (Romania): Mediamira, 1998.
- [16] I.A. Viorel, Z. Kovács, L. Szabó, "Sawyer Type Linear Motor Dynamic Modelling," in *Proceedings of the International Conference on Electrical Machines (ICEM '1992)*, Manchester (UK), 1992, pp. 697-701.
- [17] L. Szabó, I.A. Viorel, I. Chișu, Z. Kovács, "A novel double salient permanent magnet linear motor," in *Proceedings of the International Conference on Power Electronics, Drives and Motion (PCIM '1999)*, Nürnberg (Germany), 1999, pp. 285-290.
- [18] I.A. Viorel, L. Szabó, "On a three-phase modular double salient linear motor's optimal control," in *Proceedings of the 9th European Conference on Power Electronics and Applications (EPE '2001)*, Graz (Austria), 2001, p. PP00237.pdf.
- [19] L. Szabó, I.A. Viorel, "On a high force modular surface motor," in *Proceedings of the 10th International Power Electronics and Motion Control Conference (PEMC '2002)*, Cavtat & Dubrovnik (Croatia), 2002, p. 384.
- [20] I.A. Viorel, A.D. Popan, L. Szabó, R.C. Ciorba, "Direct Drive System with Two Phase Transverse Flux Disc-Type Motor," in *Proceedings of the International Conference on Power Electronics, Intelligent Motion and Power Quality (PCIM '2005)*, Nürnberg (Germany), 2005, pp. 303-308.
- [21] D.C. Popa, L. Szabó, "Improved design of a linear transverse flux reluctance motor," in *Proceedings of the 11th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM '2008)*, Braşov (Romania), 2008, pp. 137-142.
- [22] M. Rosu, P. Zhou, D. Lin, D.M. Ionel, M. Popescu, F. Blaabjerg, *et al.*, *Multiphysics Simulation by Design for Electrical Machines, Power Electronics and Drives*. Hoboken (USA): John Wiley & Sons, 2017.
- [23] L. Szabó, I.A. Viorel, V. Iancu, D.C. Popa, "Soft magnetic composites used in transverse flux machines," *Oradea University Annals, Electrotechnical Fascicle*, pp. 134-141, 2004.
- [24] W. Ouyang, S. Huang, A. Good, T. Lipo, "Modular permanent magnet machine based on soft magnetic composite," in *Proceedings of the 8th International Conference on Electrical Machines and Systems (ICEMS '2005)*, Nanjing (China), 2005, pp. 235-239.
- [25] C. Tong, F. Wu, P. Zheng, B. Yu, Y. Sui, L. Cheng, "Investigation of magnetically isolated multiphase modular permanent-magnet synchronous machinery series for wheel-driving electric vehicles," *IEEE Transactions on Magnetics*, vol. 50, no. 11, 2014.
- [26] J.D. Ede, K. Atallah, G.W. Jewell, J.B. Wang, D. Howe, "Effect of axial segmentation of permanent magnets on rotor loss in modular permanent-magnet brushless machines," *IEEE Transactions on Industry Applications*, vol. 43, no. 5, pp. 1207-1213, 2007.
- [27] I.A. Viorel, G. Henneberger, R. Blissenbach, L. Lövenstein, *Transverse Flux Machines. Their Behavior, Design, Control and Applications*. Cluj (Romania): Mediamira, 2003.
- [28] S. Su, Y. Shi, X. Yuan, K. Han, T. Cui, Y. MA, "Survey of progress in transverse flux motor," *Acta Electronica Sinica*, vol. 41, no. 11, pp. 2290-2296, 2013.
- [29] Z. Wan, A. Ahmed, I. Husain, E. Muljadi, "A novel transverse flux machine for vehicle traction applications," in *Proceedings of the 2015 Power & Energy Society General Meeting*, Denver (USA), 2015.
- [30] B. Zhang, T. Epskamp, M. Doppelbauer, M. Gregor, "A comparison of the transverse, axial and radial flux PM synchronous motors for electric vehicle," in *Proceedings of the 2014 IEEE International Electric Vehicle Conference (IEVC '2014)*, Florence (Italy) 2014.
- [31] S. Baserrah, "Theoretical and Experimental Investigations of a Permanent Magnet Excited Transverse Flux Machine with a Segmented Stator for In-Wheel Motor Applications," Ph.D. Thesis, University of Bremen, Bremen (Germany), 2014.
- [32] G. Henneberger, I.A. Viorel, *Variable Reluctance Electrical Machines*. Aachen (Germany): Shaker Verlag, 2001.
- [33] L. Someşan, E. Pădurariu, I.A. Viorel, L. Szabó, "Design of a permanent magnet flux-switching machine," in *Proceedings of the 9th International Conference ELEKTRO '2012*, Žilina - Rajecské Teplice (Slovakia), 2012, pp. 256-259.
- [34] A.S. Thomas, Z.-Q. Zhu, R.L. Owen, G.W. Jewell, D. Howe, "Multiphase flux-switching permanent-magnet brushless machine for aerospace application," *IEEE Transactions on Industry Applications*, vol. 45, no. 6, pp. 1971-1981, 2009.
- [35] A. Thomas, Z. Zhu, L. Wu, "Novel modular-rotor switched-flux permanent magnet machines," *IEEE Transactions on Industry Applications*, vol. 48, no. 6, pp. 2249-2258, 2012.
- [36] B. Štumberger, G. Štumberger, M. Hadžiselimović, A. Hamler, V. Goričan, M. Jesenik, *et al.*, "Performance comparison of three-phase flux reversal permanent magnet motors in BLDC and BLAC operation mode," *Journal of Magnetism and Magnetic Materials*, vol. 320, no. 20, pp. e896-e900, 2008.
- [37] C. Lee, R. Krishnan, N. Lobo, "Novel two-phase switched reluctance machine using common-pole E-core structure: concept, analysis, and experimental verification," *IEEE Transactions on Industry Applications*, vol. 45, no. 2, pp. 703-711, 2009.
- [38] H. Eskandari, M. Mirsalim, "An improved 9/12 two-phase E-core switched reluctance machine," *IEEE Transactions on Energy Conversion*, vol. 28, no. 4, pp. 951-958, 2013.
- [39] S.R. Mousavi-Aghdam, M.R. Feyzi, N. Bianchi, M. Morandin, "Design and analysis of a novel high-torque stator-segmented SRM," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 3, pp. 1458-1466, 2016.

- [40] M. Ruba, I.A. Viorel, L. Szabó, "Modular stator switched reluctance motor for fault tolerant drive systems," *IET Electric Power Applications*, vol. 7, no. 3, pp. 159-169, 2013.
- [41] L. Szabó, M. Ruba, "Segmental stator switched reluctance machine for safety-critical applications," *IEEE Transactions on Industry Applications*, vol. 48, no. 6, pp. 2223-2229, 2012.
- [42] M. Ruba, I. Benjia, L. Szabó, "Novel modular switched reluctance machine for safety-critical applications," in *Proceedings of the 19th International Conference on Electrical Machines (ICEM '2010)* Rome (Italy), 2010.
- [43] P.J. Lawrenson, S. Gupta, "Developments in the performance and theory of segmental-rotor reluctance motors," *Proceedings of the Institution of Electrical Engineers*, vol. 114, pp. 645-653, 1967.
- [44] L. Xu, T.A. Lipo, S.C. Rao, "Analysis of a new variable-speed singly salient reluctance motor utilizing only two transistor switches," *IEEE Transactions on Industry Applications*, vol. 26, no. 2, pp. 229-236, 1990.
- [45] R.M. Davis, "Variable reluctance rotor structures - Their influence on torque production," *IEEE Transactions on Industrial Electronics*, vol. 39, no. 2, pp. 168-174, 1992.
- [46] G.E. Horst, "Isolated Segmental Switch Reluctance Motor," US 5111096 patent, 1992.
- [47] B. Mecrow, J. Finch, E. El-Kharashi, A. Jack, "Switched reluctance motors with segmental rotors," *IEE Proceedings - Electric Power Applications*, vol. 149, no. 4, pp. 245-254, 2002.
- [48] R. Madhavan, B.G. Fernandes, "Axial flux segmented SRM with a higher number of rotor segments for electric vehicles," *IEEE Transactions on Energy Conversion*, vol. 28, no. 1, pp. 203-213, 2013.
- [49] B. Wang, D.-H. Lee, J.-W. Ahn, "Characteristic analysis of a novel segmental rotor axial field switched reluctance motor with single teeth winding," in *Proceedings of the IEEE International Conference on Industrial Technology (ICIT '2014)*, Busan (South Korea), 2014, pp. 175-180.
- [50] J.D. Widmer, R. Martin, B.C. Mecrow, "Optimization of an 80kW segmental rotor switched reluctance machine for automotive traction," *IEEE Transactions on Industry Applications*, vol. 51, no. 4, pp. 2990-2999, 2015.
- [51] D.J. Powell, G.W. Jewell, S.D. Calverley, D. Howe, "Iron loss in a modular rotor switched reluctance machine for the "More-Electric" aero-engine," *IEEE Transactions on Magnetics*, vol. 41, no. 10, pp. 3934-3936, 2005.
- [52] M. Diko, P. Rafajdus, P. Makys, P. Dubravka, L. Szabó, M. Ruba, "A novel concept of short-flux path switched reluctance motor for electrical vehicles," *Advances in Electrical and Electronic Engineering*, vol. 13, no. 3, pp. 206-211, 2015.
- [53] X. Xue, K. Cheng, Y. Bao, P. Leung, N. Cheung, "Switched reluctance generators with hybrid magnetic paths for wind power generation," *IEEE Transactions on Magnetics*, vol. 48, no. 11, pp. 3863-3866, 2012.
- [54] A. Labak, N.C. Kar, "Designing and prototyping a novel five-phase pancake-shaped axial-flux SRM for electric vehicle application through dynamic FEA incorporating flux-tube modeling," *IEEE Transactions on Industry Applications*, vol. 49, no. 3, pp. 1276-1288, 2013.
- [55] P. Andrada, E. Martínez, M. Torrent, B. Blanqué, J.I. Perat, "Novel in-wheel axial-flux segmented switched reluctance motor," in *Proceedings of the 19th European Conference on Power Electronics and Applications (EPE '17 ECCE Europe)*, Warsaw (Poland), 2017.
- [56] Z. Pan, S. Song, R. Ma, "A novel axial flux switched reluctance machine with segmented stator and rotor," in *Proceedings of the 20th International Conference on Electrical Machines and Systems (ICEMS '2017)*, Sydney (Australia), 2017.
- [57] J.H. Potgieter, F.J. Márquez-Fernández, A.G. Fraser, M.D. McCulloch, "Performance evaluation of a high speed segmented rotor axial flux switched reluctance traction motor," in *Proceedings of the 22nd International Conference on Electrical Machines (ICEM '2016)*, 2016, pp. 531-537.
- [58] W. Ding, Y. Hu, T. Wang, S. Yang, "Comprehensive research of modular E-core stator hybrid-flux switched reluctance motors with segmented and nonsegmented rotors," *IEEE Transactions on Energy Conversion*, vol. 32, no. 1, pp. 382-393, 2017.
- [59] S.-H. Mao, M.-C. Tsai, "A novel switched reluctance motor with C-core stators," *IEEE Transactions on Magnetics*, vol. 41, no. 12, pp. 4413-4420, 2005.
- [60] J.G. Amoros, P. Andrada, "Sensitivity analysis of geometrical parameters on a double-sided linear switched reluctance motor," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 1, pp. 311-319, 2010.
- [61] X. Xue, K.-W.E. Cheng, Z. Zhang, J. Lin, N. Cheung, "A novel method to minimize force ripple of multimodular linear switched reluctance actuators/motors," *IEEE Transactions on Magnetics*, vol. 48, no. 11, pp. 3859-3862, 2012.
- [62] H.S. Lim, R. Krishnan, "Ropeless elevator with linear switched reluctance motor drive actuation systems," *IEEE Transactions on Industrial Electronics*, vol. 54, no. 4, pp. 2209-2218, 2007.
- [63] E.S. Afjei, H.A. Toliyat, "A novel multilayer switched reluctance motor," *IEEE Transactions on Energy Conversion*, vol. 17, no. 2, pp. 217-221, 2002.
- [64] E.S. Afjei, A. Siadatan, H. Torkaman, "Analytical design and FEM verification of a novel three-phase seven layers switched reluctance motor," *Progress In Electromagnetics Research*, vol. 140, pp. 131-146, 2013.
- [65] A. Tenhunen, A. Arkkio, "Modelling of induction machines with skewed rotor slots," *IEE Proceedings-Electric Power Applications*, vol. 148, no. 1, pp. 45-50, 2001.
- [66] F. Daldaban, N. Ustkoyuncu, "Multi-layer switched reluctance motor to reduce torque ripple," *Energy Conversion and Management*, vol. 49, no. 5, pp. 974-979, 2008.
- [67] Y.-C. Lee, C.C. Yang, "Multi-Unit Modular Stackable Switched Reluctance Motor System with Parallely Excited Low Reluctance Circumferential Magnetic Flux loops for High Torque Density Generation," US20120001502 A1 patent application, 2012.
- [68] L. Szabó, "Permanent magnet boosted modular switched reluctance motor," *Journal of Computer Science and Control Systems*, vol. 9, no. 2, pp. 48-52, 2016.
- [69] P. Andrada, B. Blanque, E. Martinez, M. Torrent, "A novel type of hybrid reluctance motor drive," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 8, pp. 4337-4345, 2014.
- [70] W. Ding, S. Yang, Y. Hu, S. Li, T. Wang, Z. Yin, "Design consideration and evaluation of a 12/8 high-torque modular-stator hybrid excitation switched reluctance machine for EV applications," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 12, pp. 9221-9232, 2017.
- [71] T. Stallinger, W. Gruber, W. Amrhein, "Bearingless segment motor with a consequent pole rotor," in *Proceedings of the IEEE International Electric Machines and Drives Conference (IEMDC '2009)*, Miami (USA), 2009, pp. 1374-1380.

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